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Final Report Multiwavelength Monitoring of BL Lac Objects

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This is a final report to the National Aeronautics and Space Administration (NASA) concerning NASA grant NAG5-1034. This grant was awarded to Dr. C. Megan Urry of the Space Telescope Science Institute in response to a series successful IUE proposals to carry out multiwavelength observations of BL Lac objects. Over the long period of this grant, several post-docs were supported, including Paolo Padovani (now at the University of Rome), Paola Grandi (also at the University of Rome) and Joe Pesce (at STScI), as well as an STScI summer student (Amanda Marlowe Subbarao).

The grant was originally awarded on 2/1/88, with subsequent awards on 10/1/88, 10/1/89, 4/1/91, and 4/1/92; this report covers the full period of this award.

1 Research Supported under this Grant

Our IUE observations were of two kinds: (1) single-epoch multiwavelength spectroscopy of a sample of BL Lac objects and (2) multiwavelength monitoring of the UV-brightest BL Lac object, PKS 2155–304. With these campaigns we have shown that the radio-through-X-ray spectra of blazars are well-described by relativistic inhomogeneous jets closely aligned with the line of sight. Because the models are insufficiently constrained by single epoch spectra (see Urry 1993), I helped form a large group of observers and theorists to obtain well-sampled, long-term, multiwavelength (radio through gamma-ray) light curves of a few of the brightest blazars. These campaigns used a combination of space- and ground-based instrumentation, covering wavelengths in the UV (IUE), extreme UV (EUVE and WFC), X-ray (ASCA, Rosat), gamma-ray (CGRO), optical, infrared, sub-millimeter and radio bands. With some effort we obtained three significant data sets for two objects, PKS 2155–304 and 3C 279.

2 Scientific Highlights

2.1 The Gamma-Ray Luminous Superluminal Quasar 3C 279

The first blazar detected in high-energy gamma-rays was the superluminal quasar 3C 279, at the time the brightest extragalactic gamma-ray source in the sky. The observed gamma-ray luminosity was a factor of ~ 10 larger than the energy emitted in any other waveband, and it varied dramatically, by factors of 4-5 over a week or so, one of the few blazars bright enough for significant gamma-ray variability to be detected. 3C 279 is usually bright enough to be detected with IUE and typical X-ray satellites, and has been well monitored at most wavelengths, and has been well mapped with VLBI for more than a decade.

For these reasons, I organized intensive monitoring of 3C 279 at gamma-ray and other wavelengths (with Laura Maraschi, and Ann Wehrle) during three weeks in late 1992. 3C 279 was at an historically faint level and the upper limit to its gamma-ray flux was a factor of ~ 30 below the original detection 18 months earlier. The decrease was much larger in gamma-ray flux than in optical/UV flux, roughly consistent with the SSC model but also with a correlated change in relativistic electron energy and external seed photons or with a decrease in bulk relativistic speed. Since the temporal sampling was sparse, the two single-epoch spectra might not represent a single variability event with associated decay, so we continue to monitor this object.

2.2 Jets in Low-Luminosity Blazars

2.2.1 PKS 2155–304: The First Campaign

I led a large multiwavelength monitoring effort (with Laura Maraschi and Rick Edelson) to determine whether optical, UV, and X-ray emission in blazars are correlated. Our intensive multiwavelength monitoring of PKS 2155–304 in November 1991 revealed a number of unprecedented, and in some cases surprising, results:

- We detected extremely rapid variations at optical, UV, and X-ray wavelengths, with time scales as short as a day and overall changes by a factor of two in a one-month period. Previous monitoring of blazars at UV wavelengths had clearly been undersampled by large factors. The fastest variations we observed had $\sim$ 10–30% amplitude and the autocorrelation function of these flares had a peak at about ~ 0.7 days.

- Variations were closely correlated at optical, UV, and X-ray wavelengths. Because of the simultaneity of the optical and UV variations, we could rule out an accretion disk origin of the UV continuum.

- The amplitude of variation was essentially independent of wavelength, in contrast to what is expected from a synchrotron flare in a jet, for which the amplitude of variations should increase with energy as losses become more important.

- The X-rays led the UV by a small but significant amount, roughly 2-3 hours. For likely jet models, a propagating shock should have caused a longer delay and an autocorrelation function that broadened with increasing wavelength, which were not observed.

- The fact that the X-ray lead time was roughly an order of magnitude shorter than the variability time scale suggested some kind of flattened geometry, as expected from a transverse shock in a jet.

2.2.2 PKS 2155–304: The Second Campaign

Because of the unexpectedness and uniqueness of the first results, I proposed and carried out a longer period of intensive monitoring (with Laura Maraschi, my post-doc Joe Pesce, and a large number of co-investigators), with sampling matched to the now-known variability characteristics and with far fewer temporal gaps in coverage. We obtained IUE, EUVE, ASCA, and Rosat data, as well as increased coverage from the ground. The results of this second campaign were more startling still (see references below; also, Urry et al., Pian et al., Kii et al., Marshall et al., and Pesce et al., in preparation):

- The character of the variations at UV and X-ray wavelengths was dramatically different than in the first campaign. While still rapid, variations at UV, extreme UV, and X-ray wavelengths were isolated flares rather than the "quasi-periodic" low-amplitude variations seen in the first campaign.

- The overall variability amplitude was much higher than in the first epoch, particularly in the X-ray band, where the flux rose and fell by a factor of ~ 2.5 in about a day.

- The variability was strongly wavelength dependent. The UV flare we can most plausibly identify with the strong X-ray flare has an amplitude of $\sim 40\%$, double that of the first epoch but still a factor of ~ 6 smaller than the X-ray flare.

- The X-ray flare appears to lead the EUV and UV fluxes by 1 and 2 days, respectively, an order of magnitude longer than the lag detected in the first epoch. (Because of the limited X-ray coverage, however, there is an inevitable ambiguity in the correlation.) The longer lag and the neat progression of the flare from X-ray to EUV to UV wavelengths are exactly as expected from a synchrotron flare caused by a shock propagating outward along the jet.

- A UV flare at the onset of the IUE observation has a doubling time of order 1 hour, faster than any UV variability ever seen in an extragalactic object, and comparable to the fastest X-ray variability time scale seen in blazars.

In short, the results of the second campaign look very much like the synchrotron flare expected in the first place. The contrast between the variations seen in the two campaigns is so dramatic that different physical processes must be involved. In particular, I believe the second episode of variable amplitude flaring is due to a shock in the relativistic jet, while the first episode of achromatic, low-amplitude variability could be due to micro-lensing of the relativistic jet by hundreds of stars in the core of a galaxy approximately half-way to PKS 2155–304. We are now preparing for publication papers describing the remarkable second-epoch light curves, and we have also completed another paper describing the possibilities for micro-lensing.

To date, no group has equivalent data for any blazar.

3 Publications Resulting from NAG5-1034

The following refereed publications were supported by grant NAG5-1034:

- "Multiwavelength Monitoring of the BL Lacertae Object PKS 2155-304. IV. Multi-Wavelength Analysis" R. A. Edelson, J. Krolik, G. Madejski, L. Maraschi, C. M. Urry, W. Brinkmann, T. J.L. Courvoisier, J. Ellithorpe, K. Horne, A. Treves, S. Wagner, W. Wamsteker, R. Warwick, H. D. Aller, M. F. Aller, M. Ashley, A. Blecha, P. Bouchet, P. Bratschi, J. N. Bregman, M. Carini, A. Celotti, M. Donahue, E. Feigelson, A. V. Filippenko, H. Fink, I. George, I. Glass, J. Heidt, J. Hewitt, P. Hughes, R. Kollgaard, Y. Kondo, A. Koratkar, K. Leighly, A. Marscher, P. G. Martin, T. Matheson, H. R. Miller, J. C. Noble, P. O'Brien, E. Pian, G. Reichert, J. M. Saken, J. M. Shull, M. Sitko, P. S. Smith, W.-H. Sun, and G. Tagliaferri, 1995, ApJ, 438, 120

- "Multiwavelength Monitoring of the BL Lacertae Object PKS 2155–304. III. Ground-Based Observations in November 1991" T. J.-L. Courvoisier, A. Blecha, P. Bouchet, P. Bratschi, M. T. Carini, M. Donahue, R. Edelson, E. D. Feigelson, A. V. Filippenko, I. S. Glass, J. Heidt, R. I. Kollgaard, T. Matheson, H. R. Miller, J. C. Noble, K. Sekiguchi, P. S. Smith, C. M. Urry, and S. J. Wagner, 1995, ApJ, 438, 108

- "Multiwavelength Monitoring of the BL Lacertae Object PKS 2155–304. II. The ROSAT Observations" W. Brinkmann, L. Maraschi, A. Treves, C. M. Urry, R. Warwick, J. Siebert, S. Wagner, R. Edelson, H. Fink, and G. Madejski, 1994, A&A, 288, 433

- "Multiwavelength Monitoring of the BL Lacertae Object PKS 2155–304. I. The IUE Campaign" C. M. Urry, L. Maraschi, R. Edelson, A. Koratkar, J. Krolik, G.

Madejski, E. Pian, G. Pike, G. Reichert, A. Treves, W. Wamsteker, R. Bohlin, J. Bregman, W. Brinkmann, L. Chiappetti, T. Courvoisier, A. V. Filippenko, H. Fink, I. M. George, Y. Kondo, P. G. Martin, H. R. Miller, P. O'Brien, J. M. Shull, M. Sitko, A. E. Szymkowiak, G. Tagliaferri, S. Wagner, and R. Warwick, 1993, ApJ, 411, 614

- "Accretion Disk Emission from a BL Lacertae Object" A. Wandel and C. M. Urry, 1991, ApJ, 367, 78

- "Fanaroff-Riley I Galaxies as the Parent Population of BL Lacertae Objects. I. X-Ray Constraints" P. Padovani and C. M. Urry, 1990, ApJ, 356, 75

- "Active Galactic Nuclei" C. M. Urry, 1988, in *Multiwavelength Astrophysics*, ed. F. Cordova, (Cambridge: Cambridge University Press), p. 279

- "An Evolving Relativistic Jet Model for the BL Lacertae Object Mrk 421" S. L. Mufson, D. J. Hutter, Y. Kondo, C. M. Urry, and W. Z. Wisniewski, 1990, ApJ, 354, 116

- "Eight Years of Ultraviolet Spectra of the Variable BL Lacertae Object PKS 2155–304" C. M. Urry, Y. Kondo, K. R. H. Hackney, and R. L. Hackney, 1988, ApJ, 330, 791

In addition, Paolo Padovani published published work on a related topic which he completed while funded under this grant:

- "Luminosity Functions, Relativistic Beaming, and Unified Theories of Radio Sources" P. Padovani and C. M. Urry, 1992, ApJ, 387, 449

- "Altered Luminosity Functions for Relativistically Beamed Objects. II. Distribution of Lorentz Factors and Complex Parent Luminosity Functions" C. M. Urry and P. Padovani, 1991, ApJ, 371, 60

- "Fanaroff-Riley I Galaxies as the Parent Population of BL Lacertae Objects. III. Radio Constraints" C. M. Urry, P. Padovani, and Stickel, M., 1991, ApJ, 382, 501

- "Rapid Ultraviolet Variability in the BL Lacertae Object PKS 2155–304" R. A. Edelson, J. M. Saken, G. F. Pike, C. M. Urry, I. M. George, R. S. Warwick, H. R. Miller, M. T. Carini, and J. R. Webb, 1991, ApJ (Letters), 372, L9

- "Fanaroff-Riley I Galaxies as the Parent Population of BL Lacertae Objects. II. Optical Constraints" P. Padovani and C. M. Urry, 1991, ApJ, 368, 373

- "The Complete Sample of 1 Jansky BL Lacertae Objects. I. Summary Properties" M. Stickel, P. Padovani, C. M. Urry, J. Fried, and H. Kühr, 1991, ApJ, 374, 431

Paola Grandi also published work on a related topic completed while she was partially funded under this grant:

- "3C279 Multiwavelength Monitoring. II. Ground-Based Campaign" 1996, P. Grandi, C. M. Urry, L. Maraschi, A. E. Wehrle, G. M. Madejski, M. F. Aller, H. D. Aller, C. D. Bailyn, T. J. Balonek, T. H. Bock, I. S. Glass, S. J. Litchfield, I. M. McHardy, J. S. Mulchaey, H.-P. Reuter, E. I. Robson, A. C. Sadun, W. Sherry, H. Steppe, J. A. Steven, H. Teräsranta, M. Tornikoski, and S. J. Wagner, ApJ, 459, 73

- "The 1993 Multiwavelength Campaign on 3C279. I. The Radio to Gamma-Ray Energy Distribution in the Low State" L. Maraschi, P. Grandi, C. M. Urry, A. E. Wehrle, G. Madejski, H. H. Fink, G. Ghisellini, R. C. Hartman, A. Koratkar, E. Pian, H.-C. Thomas, A. Treves, M. F. Aller, H. D. Aller, C. D. Bailyn, T. J. Balonek, H. Bock, W. Collmar, I. S. Glass, S. J. Litchfield, I. M. McHardy, R. Méndez, J. Pesce, H. P. Reuter, E. I. Robson, H. Steppe, J. A. Stevens, H. Teräsranta, and S. J. Wagner, 1994, ApJ (Letters), 435, L91

- "Nonthermal Pair Models, Reflection and X-Ray Spectral Variability" P. Grandi, C. Done, and C. M. Urry, 1994, ApJ, 428, 599

Similarly, Joe Pesce, has published work on a related topic completed while he was partially funded under this grant:

- "Redshifts of Southern Radio Galaxies" 1995, R. Scarpa, R. Falomo, and J. E. Pesce, A&A, in press

- "Host galaxy and environment of the BL Lacertae Object PKS 0548–322: Observations with subarcsecond resolution" 1995, R. Falomo, J. E. Pesce, and A. Treves, ApJ, 438, L9

- "Environmental Properties of BL Lac Objects" 1995, J. E. Pesce, R. Falomo, and A. Treves, AJ, 110, 1554

The following invited review papers and/or book chapters were based in part on work supported by this grant:

- "Blazars, the Most Violent Active Galaxies" C. M. Urry, 1996, AAAS Annual Meeting and Science Innovation Exposition, 162nd National Meeting of the AAAS, ed. Michael S. Strauss, et al., p. S-48

- " An Overview of Blazar Variability" C. M. Urry, 1996, in *Blazar Variability*, (Proc. Conference in Miami, February 1996), ed. J. Webb, in press

- "Jets in Active Galactic Nuclei" C. M. Urry, 1993, in *Frontiers of Space and Ground-based Astronomy*, ed. W. Wamsteker, M. S. Longair, and Y. Kondo, (Dordrecht: Kluwer), p. 335

- "Multiwavelength Monitoring of Active Galactic Nuclei" C. M. Urry,1993, Adv. Space Res., 13, 573

Finally, the following papers have been presented at or submitted for conferences:

- "Multiwavelength Observations of PKS 2155-304 during May 1994: The Ground-based Campaign" J. E. Pesce, C. M. Urry, and L. Maraschi, 1996, in*Blazar Variability*, (Proc. Conference in Miami, February 1996), ed. J. Webb
- " Multiwavelength Monitoring of the BL Lac Object PKS 2155-304. The May 1994 IUE Campaign" E. Pian, C. M. Urry, L. Maraschi, et al., 1996, *Blazar Variability*, (Proc. Conference in Miami, February 1996), ed. J. Webb
- "Observations of Blazars with ASCA" F. Makino, R. Edelson, R. Fujimoto, T. Kii, E. Idesawa, K. Makishima, T. Takahashi, K. Sasaki, T. Kamae, H. Kubo, D. Mathis, M. Tashiro, H. Teräsranta, and C. M. Urry, 1995, in *Roentgenstrahlung in the Universe*, (Proc. Rosat Conf., Wurzburg, Sep 1995), in press
- "Rapid Multiwavelength Flaring of the BL Lac Object PKS 2155–304" C. M. Urry, J. E. Pesce, R. M. Sambruna, A. Treves, E. Pian, L. Maraschi, T. Kii, K. Sasaki, F. Makino, R. Fujimoto, C. Otani, F. Makino, M. Tashiro, T. Takahashi, H. Marshall, G. Madejski, S. Penton, and J. M. Shull, 1995, BAAS, 26, 1467
- "The Multifrequency Spectra of Blazars" R. M. Sambruna, C. M. Urry, L. Maraschi, and G. Ghisellini, 1994, in *The Multi-Mission Perspective* (High Energy Astrophysics Division Meeting of the American Astronomical Society, Napa Valley, November 1994), p. 106
- "Multiwavelength Observations of the BL Lac Object PKS 2155–304" J. E. Pesce, C. M. Urry, R. M. Sambruna, A. Treves, E. Pian, L. Maraschi, T. Kii, K. Sasaki, F. Makino, R. Fujimoto, M. Tashiro, H. Marshall, G. Madejski, S. Penton, and J. M. Shull, 1994, in *The Multi-Mission Perspective* (High Energy Astrophysics Division Meeting of the American Astronomical Society, Napa Valley, November 1994), p. 107
- "A Movie of PKS 2155–304 in Living Ultraviolet Color" C. M. Urry, W. Welsh, D. Berry, Z. Levay, W. Feimer, A. Koratkar, L. Maraschi, G. Madejski, and R. Edelson, 1993, BAAS, 25, 792
- "Correlated Multi-Wavelength Variability in the BL Lacertae Object PKS 2155–304" R. Edelson, J. Krolik, L. Maraschi, G. Madejski, G. Pike, W. Brinkmann, C. M. Urry, K. Horne, T. Courvoisier, J. Hewitt, and J. Ellithorpe, 1992, BAAS, 24, 1209

- "Time-Dependent Inhomogeneous Jet Models for BL Lac Objects" A. T. Marlowe, C. M. Urry, and I. M. George, 1992, in *Testing the AGN Paradigm*, ed. S. S. Holt, S. J. Neff, and C. M. Urry, (New York: AIP), p. 447

- "Unification of Radio-Loud AGN" C. M. Urry and P. Padovani, 1992, in *Testing the AGN Paradigm*, ed. S. S. Holt, S. J. Neff, and C. M. Urry, (New York: AIP), p. 459

- "Luminosity Functions, Relativistic Beaming, and Unified Theories of AGN" P. Padovani and C. M. Urry, 1992, in *Physics of Active Galactic Nuclei*, ed. W. J. Duschl, S. J. Wagner, (Berlin: Springer Verlag), p. 642

- "EUV Observations of AGNs" P. M. Gondhalekar, K. A. Pounds, S. Sembay, J. Sokoloski, C. M. Urry, L. Matthews, and J. Quenby, 1992, in *Physics of Active Galactic Nuclei*, ed. W. J. Duschl, S. J. Wagner, (Berlin: Springer Verlag), p. 52

- "Unification of Radio Galaxies and Quasars" P. Padovani and C. M. Urry, 1992, BAAS, 23, 1344

- "Intensive UV Monitoring of the BL Lac Object PKS 2155–304" C. M. Urry, L. Maraschi, R. Bohlin, A. Koratkar, L. Chiappetti, E. Pian, A. Treves, R. Edelson, G. Madejski, G. Pike, G. Reichert, J. Krolik, and W. Wamsteker, 1992, BAAS, 24, 744

- "Final Archive Definition Committee Reports" J. Linsky, et al. (with C. M. Urry) 1992, NASA IUE Newsletter, 48, 1

- "Multiwavelength Monitoring of the BL Lac Object PKS 2155–304. I. IUE Observations" C. M. Urry, L. Maraschi, R. Edelson, A. Koratkar, G. Madejski, E. Pian, G. Pike, G. Reichert, A. Treves, W. Wamsteker, R. Bohlin, W. Brinkmann, L. Chiappetti, T. Courvoisier, A. V. Filippenko, H. Fink, I. M. George, Y. Kondo, J. Krolik, P. O'Brien, M. Shull, M. Sitko, A. E. Szymkowiak, G. Tagliaferri, S. Wagner, and R. Warwick, 1992, in *Science with the HST*, ed. P. Benvenuti and Ethan Schreier, (ESO Conf. Proc. 44), p. 89

- "Multifrequency Observations of Quasar 3C279 in Outbursts" F. Makino, T. Kii, K. Hayashida, T. Ohashi, M. J. L. Turner, A. C. Sadun, C. M. Urry, G. Neugebauer, H. Terasranta, and M. F. Aller, 1991, in *Variability of Active Galactic Nuclei*, ed. H. R. Miller and P. J. Wiita, (Cambridge University Press), p. 13.

- "Accretion Disk Emission from a BL Lacertae Object" A. Wandel and C. M. Urry, 1991, in *Structure and Emission Properties of Accretion Disks*, ed. C. Bertout, S. Collin, J-P. Lasota, and J. Tran Thanh Van, (Editions Frontieres), p. 553

- "Accretion Disk Emission from a BL Lacertae Object" A. Wandel and C. M. Urry, 1991, in *Structure and Emission Properties of Accretion Disks*, ed. C. Bertout, S. Collin, J-P. Lasota, and J. Tran Thanh Van, (Editions Frontieres), p. 553
- "Modeling the IUE Noise Function" C. M. Urry, M. J. Berghoffen, and R. A. Edelson, 1990, NASA IUE Newsletter, 46, 88
- "Active Galactic Nuclei: A Multiwavelength View" C. M. Urry,1990, BAAS, 21, 1096 (Invited)
- "Accretion Disk Emission from a BL Lacertae Object" C. M. Urry and A. Wandel, 1990, in *Evolution in Astrophysics*, (ESA SP-310), p. 561
- "Relativistic Beaming and the Parent Population of BL Lacertae Objects" C. M. Urry and P. Padovani, 1990, in BAAS, 22, 872
- "Accretion Disk Models of BL Lac Objects" A. Wandel and C. M. Urry, 1989, in *BL Lac Objects*, ed. L. Maraschi, T. Maccacaro and M.-H. Ulrich (Berlin: Springer-Verlag), p. 388
- "Star Formation in Normal and Barred Cluster Spirals" 1995, C. Moss, M. Whittle, J. E. Pesce, and H. Navaro, *Astrophysical Letters and Communications*, 31, 215
- "The cluster environment of BL Lac Objects" 1994, R. Falomo, J. E. Pesce, ESO Messenger, 78, 30

FINAL PATENT/INVENTION REPORT

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Patents/Inventions Developed: NONE